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Low Energy Supersymmetry and the Tevatron Bottom Quark Cross Section

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Contents:

hep-ph/0012001

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1. Motivation and Constraints

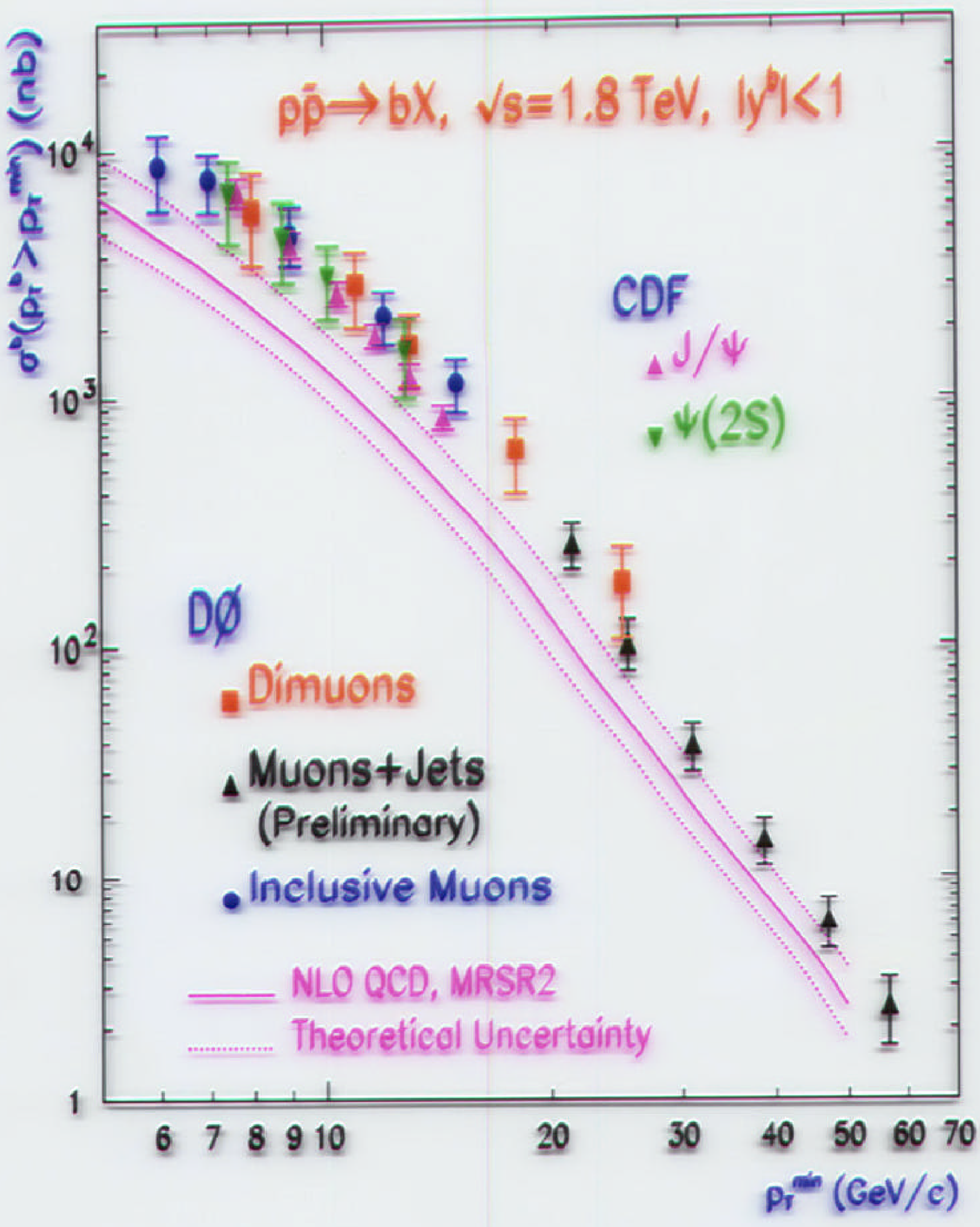
- Measured cross section for bottom quark production at hadron colliders exceeds the (central value of) predictions of next-to-leading order (NLO) QCD by about a factor of 2 [→ Fig.]
- NLO contributions are large, and it is not excluded that further NNLO effects may do the trick, but ...
- Longstanding discrepancy has resisted satisfactory resolution within the SM → room for new physics?
- Propose a possible explanation within the context of the minimal supersymmetric standard model (MSSM): assume existence of a light color-octet, spin-1/2 gluino ($\tilde{g}$) and a light color-triplet spin-0 bottom squark ($\tilde{b}$):

$$p + \bar{p} \to \tilde{g} + \tilde{g} + X,$$

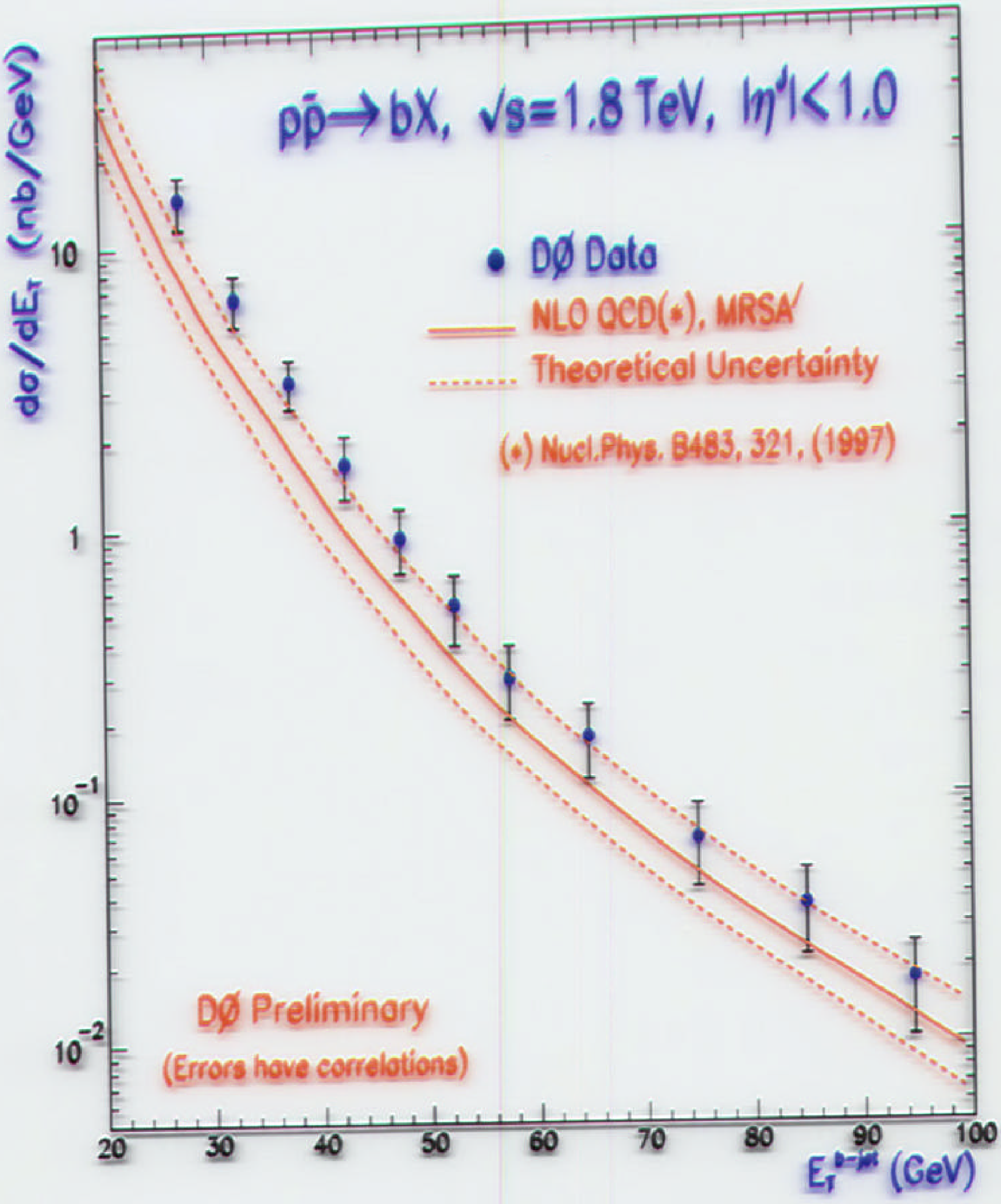
$$\tilde{g} \to b + \tilde{b}$$

- Masses constrained by "fit" to the hadron collider data:
  - $m_{\tilde{g}} \simeq 12$ to 16 GeV; $m_{\tilde{b}} \simeq 2$ to 5.5 GeV
- $\tilde{b}$ is long-lived on the scale of colliders or it decays hadronically (via R-parity violation?)

INTEGRATED TRANSVERSE MOMENTUM SPECTRUM FOR b QUARKS



DIFFERENTIAL b-JET TRANSVERSE MOMENTUM DISTRIBUTION



LEP Constraints on Bottom Squark Couplings

(Carena, Heinemeyer, Wagner, and Weiglein, hep-ph/0008023)

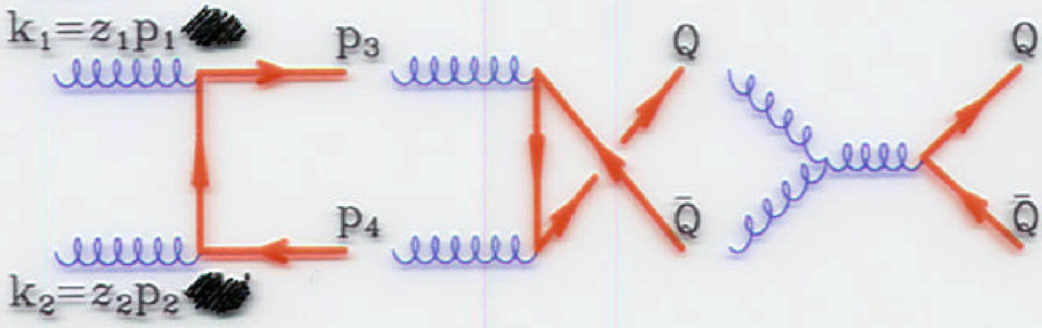
- Light $\widetilde{b}$ would be ruled out by LEP1 data unless its coupling to the Z boson is small
- Squark couplings to the Z depend on the mixing angle $\theta_{\tilde{b}}$
- Let $\sin\theta_{\tilde{b}} = s_{\tilde{b}}$ be the left-handed component of the lightest $\tilde{b}$ mass eigenstate; $s_W^2 = \sin^2\theta_W$
- Coupling $g_{Z\tilde{b}_1\tilde{b}_1} \sim [T_3\, s_{\tilde{b}}^2 - Q_{\tilde{b}}\, s_W^2]$
  ($T_3 = -1/2$; $Q_{\tilde{b}} = -1/3$)
- Coupling to Z vanishes for $s_{\tilde{b}}^2 \sim 1/6$
- Thus, if the light bottom squark is an appropriate mixture of left-handed and right-handed bottom squarks, tree-level coupling to the Z can be made small
- $Z - \widetilde{b}_1 - \widetilde{b}_2$, $Z - \widetilde{b}_2 - \widetilde{b}_2$ couplings survive in this limit
- Require $m_{\widetilde{b}_2} > 200$ GeV to avoid
  $e^+e^- \to Z^* \to \widetilde{b}_1 + \widetilde{b}_2$

Further Considerations

- For a small range of values of $s_{\widetilde{b}}$, Z-peak observables Γ_Z, R_c, R_ℓ, R_b, A^b, A^b_{FB} are fit about as well as in the SM
- A light $\widetilde{b}$ with some $\widetilde{b}_L$ component will contribute to $\Delta\rho$ (T parameter), depending on the $\widetilde{t}$ sector; constrains the top squark mass to be light ($m_{\widetilde{t}} \sim m_t$)
- Exclusion by CLEO of a light $\widetilde{b}$ with mass 3.5 to 4.5 GeV does not apply since their analysis focuses on $\tilde{b} \to cl\tilde{\nu}$ and $\tilde{b} \to cl$
- ALEPH LEP analysis of 4 jet events excludes a $\tilde{g}$ with $m_{\tilde{g}} < 6.5$ GeV, but not gluinos in the mass range of interest to us. Light $\widetilde{b}$ is not excluded by 4 jet analysis (Z. Phys C76, 1 (1997))
- Dedes and Dreiner use the renormalization group method to argue that the existence of a light $\widetilde{b}$ goes hand-in-hand with a comparatively light $\tilde{g}$, $m_{\tilde{g}} \sim 10$ GeV (hep-ph/0009001)

2. Production Processes

- Pair production of $Q\bar{Q} = b\bar{b}, \tilde{g}\tilde{g}$ via gg scattering in LO QCD:



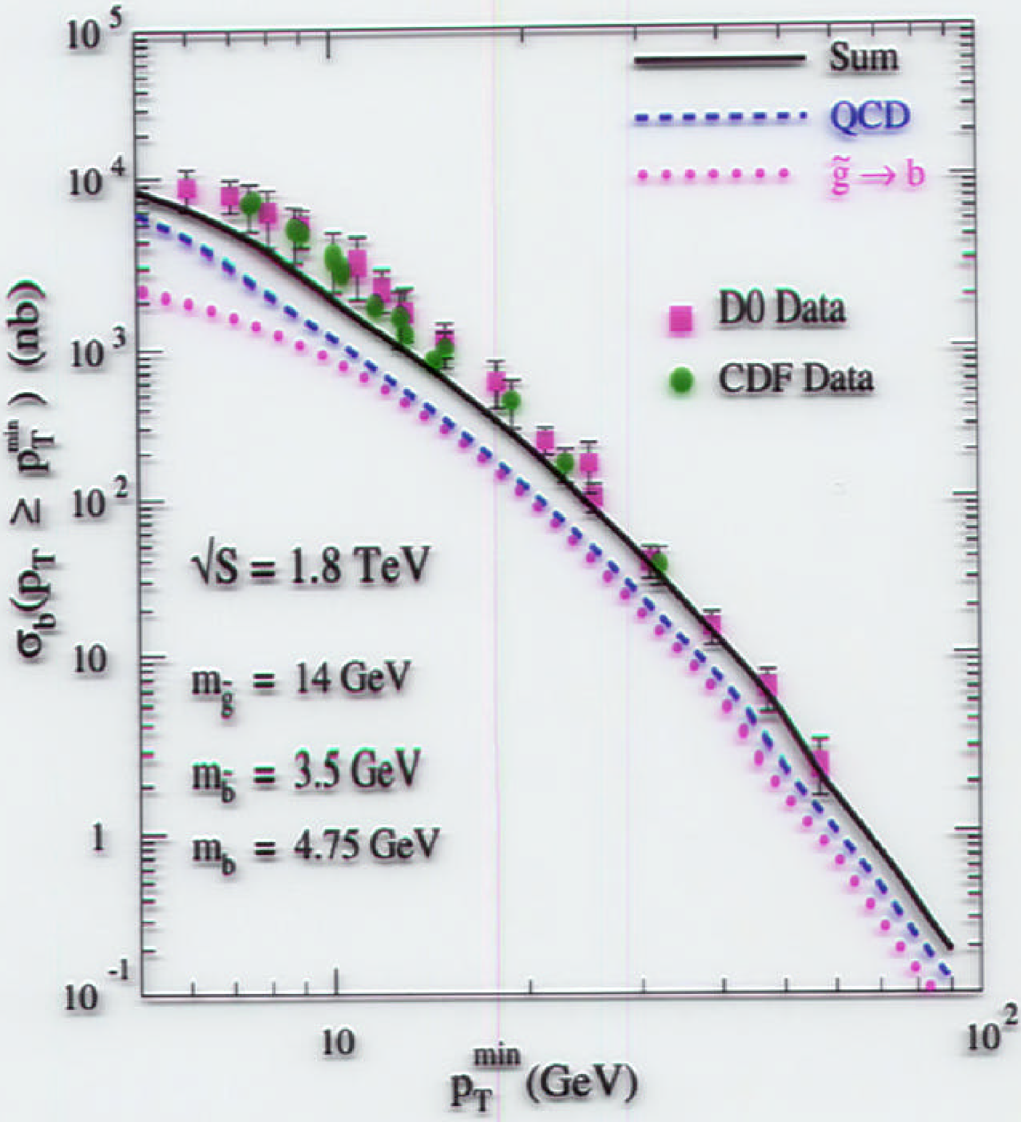
- Second set of LO diagrams for $q\bar{q}$ initial state, but gg scattering dominates at Tevatron energies for the masses we consider. All contributions are included in our numerical calculations

- QCD NLO calculation of b cross section with CTEQ4M parton densities; renormalization/factorization scale $\mu = \sqrt{m_b^2 + p_{Tb}^2}$; SUSY-QCD contributions to b production are not included – not available and expected to be small

- Fully differential NLO calculation of $\tilde{g}$ pair production and decay $\tilde{g} \to b + \tilde{\bar{b}}$ does not exist; $\tilde{g}$ contribution computed at LO; $\mu = \sqrt{m_{\tilde{g}}^2 + p_{T\tilde{g}}^2}$; and multiplied by an overall NLO enhancement (K) factor

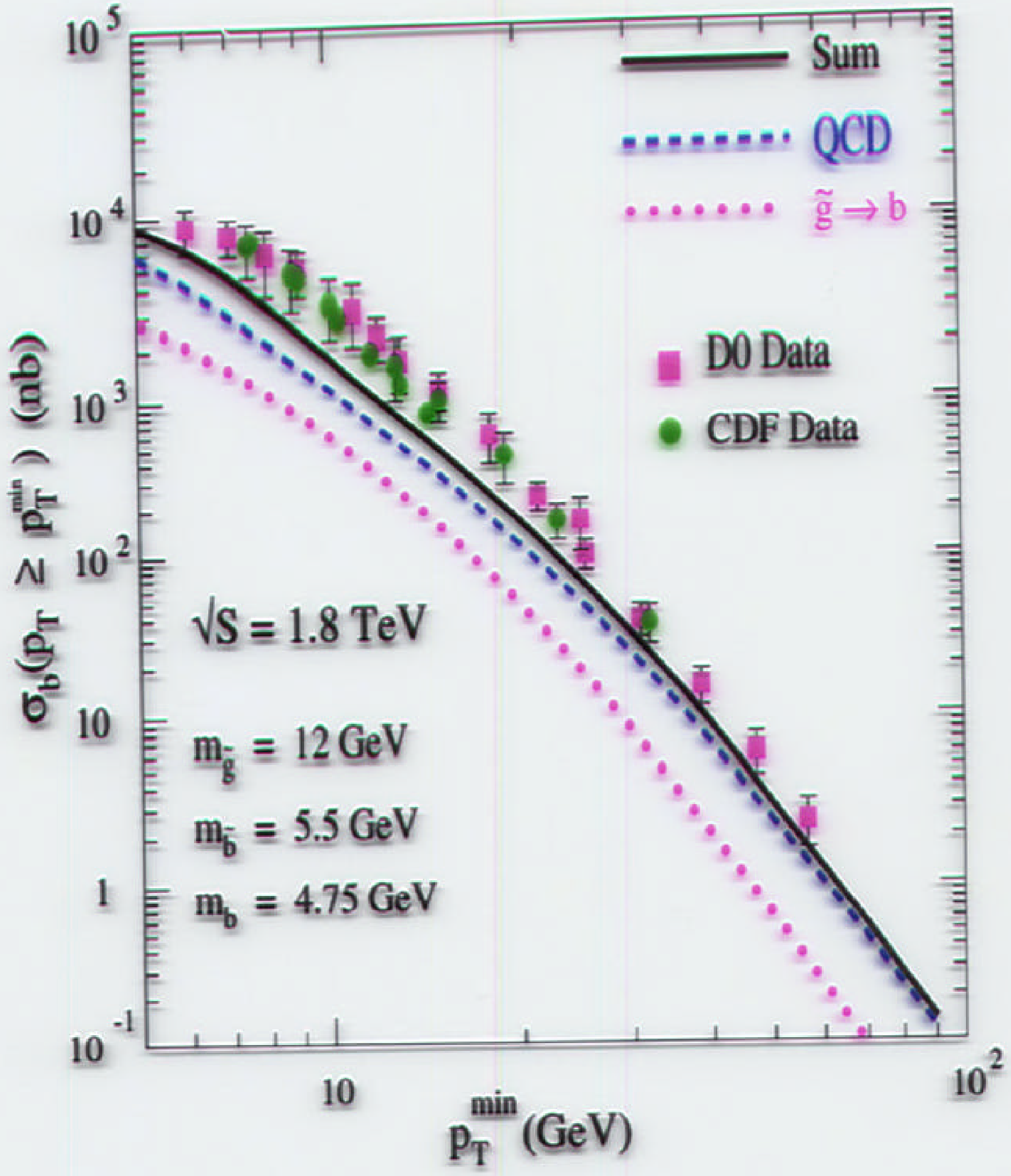
- $g + b \to \tilde{g} + \tilde{\bar{b}}$ contributes less than 2% of $\sigma_{b\bar{b}}^{\rm qcd}$

3. Differential Cross Section



- Values of $m_{\tilde{g}} \simeq 12$ to 16 GeV produce p_{Tb} spectra that are enhanced near $p_{Tb}^{\min} \simeq m_{\tilde{g}}$ where data deviate most from pure QCD; light $\tilde{g}$ necessary to obtain a b cross section comparable to the pure QCD rate
- The rapidity distribution of the b's and the azimuthal angular distributions $\Delta\phi$ between the final b's are very similar after p_T selections in the SUSY and pure QCD cases

ANOTHER SET OF MASSES



- Choice of $m_{\tilde{b}}$ impacts the kinematics of the b; large values of $m_{\tilde{b}}$ reduce the cross section and result in p_{Tb} spectra that agree less well with data; choices of $m_{\tilde{b}}$ and $m_{\tilde{g}}$ are coupled

4. Ratio of Same-Sign to Opposite-Sign Leptons

- QCD processes produce $b\bar{b}$ pairs
- Majorana $\tilde{g}$ decays into b and $\bar{b}$
- $\tilde{g}\tilde{g}$ pair production will generate bb and $\bar{b}\bar{b}$ pairs as well as $b\bar{b}$ pairs $\rightarrow$ potential increase in same-sign lepton pairs, and apparent increased rate of $B\bar{B}$ mixing
- For highly relativistic $\tilde{g}$'s, $\tilde{g}$'s helicity is nearly the same as its chirality $\rightarrow$ selection of $\tilde{g}$'s with $p_{T\tilde{g}} >> m_{\tilde{g}}$ reduces same sign b's.
- Cuts chosen in Tevatron run I $\Rightarrow$ principally unpolarized $\tilde{g}$'s and thus, at production, $N(bb + \bar{b}\bar{b}) \simeq N(b\bar{b})$
- Analyze effect of the new SUSY contribution in terms of $\bar{\chi}$
  - $\bar{b} \Rightarrow B^o, B_s, \Lambda_b, B^+$
    $\rightarrow \ell^+$, "right sign", with probability $1 - \bar{\chi}$
    $\rightarrow \ell^-$, "wrong sign", with probability $\bar{\chi}$
  - Define LS, same-sign lepton fraction
  - Conventional $b\bar{b}$ pair production
    $\rightarrow LS_c = 2\bar{\chi}(1 - \bar{\chi})$
- New expression

- Definition:

$$G \equiv \frac{\sigma_{\tilde{g}\tilde{g}}}{\sigma_{\rm qcd}}$$

- Ratio G is determined in the (cut) region of phase space where LS is measured; CDF: $p_T > 6.5$ GeV and $y_b \leq 1$, both b's

- Hadron collider experiments measure

$$\bar{\chi}_{\rm eff} \equiv \frac{\bar{\chi}}{\sqrt{1+G}} + \frac{1}{2}\left[1 - \frac{1}{\sqrt{1+G}}\right]$$

- For $m_{\tilde{g}} = 14, 16$ GeV, we compute $G = 0.37, 0.28$
- Adopt average value from PDG: $\bar{\chi} = 0.118 \pm 0.005$
- Predict: $\bar{\chi}^{\rm th}_{\rm eff} = 0.17, m_{\tilde{g}} = 14{\rm GeV}$

$$\bar{\chi}^{\rm th}_{\rm eff} = 0.16, m_{\tilde{g}} = 16{\rm GeV}$$

- Large QCD theoretical uncertainties (scale dependence, no fully NLO calculation of $\tilde{g}$ pair production and decay): $\delta\bar{\chi}_{\rm eff} \simeq \pm 0.02$
- CDF measurement is higher than the world average (PRD 55, 2546 (1997)):

$$\bar{\chi}^{\rm exp} = 0.131 \pm 0.020 \pm 0.016$$

5. Other Implications and Remarks

5 a) Hadron Reactions

- Most clearcut expectation is pair production of like-sign B's: B^+B^+ and B^-B^-
- Very precise measurement of $\bar{\chi}$ at run II is desirable; fraction of b's from gluinos also changes with p_{Tb} so there should be a change of $\bar{\chi}$ with the cut on p_{Tb}
- The b jet from $\tilde{g}$ decay into $b\tilde{\bar{b}}$ will contain the $\tilde{\bar{b}} \to$ unusual material in some fraction of the $b\bar{b}$ data sample from the $\tilde{\bar{b}}$ in the b jet
- Existence of light $\tilde{\bar{b}}$'s means they will be pair-produced directly $\to$ slight increase ($< 1\%$) in the hadronic dijet rate
- Increased rate of b production at HERA ($\gamma^* g \to b\bar{b}$) and in $\gamma\gamma \to b\bar{b}$ at LEP, but perhaps too small if current data are confirmed; NLO calculation and better parton densities of photons are needed.

5 b) $\widetilde{b}$ lifetime and observability

- Simple scaling from μ or τ lepton decay, $\tau^{-1} \sim m^5$, suggests $\tau_{\tilde{b}} \sim 10^{-14}$ s ($c\tau \sim 3\mu\mathrm{m}$) for $m_{\tilde{b}} = 3.5$ GeV
- But, R-parity conservation does not permit $\widetilde{b}$ decay unless there is an even lighter LSP
- Limits on baryon-number-violating R-parity-violating couplings λ'' are relatively weak for 3rd generation $\widetilde{q}$'s: $\lambda'' < 0.5$ to 1 (Allanach Dedes Dreiner, PR D60, 075014 (1999))
- MSSM superpotential with baryon-number-violating R-parity-violation term

$$\mathcal{W}_{\not{R}_p} = \lambda''_{ijk} U_i^c D_j^c D_k^c$$

- U_i^c and D_i^c are right-handed-quark singlet chiral superfields; i, j, k are generation indices
- Possible $\not{R}_p$ decay channels are $123 : \bar{\widetilde{b}} \to u + s$, $213 : \bar{\widetilde{b}} \to c + d$, and $223 : \bar{\widetilde{b}} \to c + s$

$$\Gamma(\widetilde{b} \to jj) = \frac{m_{\widetilde{b}}}{2\pi} \sin^2 \theta_{\widetilde{b}} \sum_{j<k} |\lambda''_{ij3}|^2$$

- If $m_{\tilde{b}} = 3.5$ GeV, $\Gamma(\widetilde{b} \to ij) = 0.08 |\lambda''_{ij3}|^2$ GeV
- Unless λ''_{ij3} is extremely small, the $\widetilde{b}$ will decay quickly and leave soft jets in the cone around the b; jets with an extra c are possibly disfavored by CDF; detailed simulation is needed

5 b) $\tilde{b}$ lifetime and observability, continued

- Suppose the $\tilde{b}$ is relatively "stable", what could happen?
  - $\tilde{b}$ picks up a light $\bar{u}$ and becomes a $\tilde{B}^-$ "mesino" with $J = 1/2$, the superpartner of the B meson, a hadron with mass ~ 3 to 7 GeV
  - The mesino is not a muon but could fake a heavy muon as it exits the muon chambers; → extra "muons" in a fraction of the $b\bar{b}$ event sample, with tracks that left some trace in the hadron calorimeter?
  - The mesino has baryon number 0 but acts like a heavy $\bar{p}$ – perhaps detectable with a TOF detector in run II
  - Detailed analyses should be done at hadron colliders to verify what ranges of $\tilde{b}$ masses and lifetimes may be allowed/disfavored, similar to that done for $\tilde{g}$'s (c.f. Baer, Cheung, Gunion, PRD 59, 075002 (1999))
  - $\tilde{b}$-onia
  - $\tilde{b}$'s will be made in cosmic ray collisions or in particle detectors → weird isotopes?

5 c) α_S

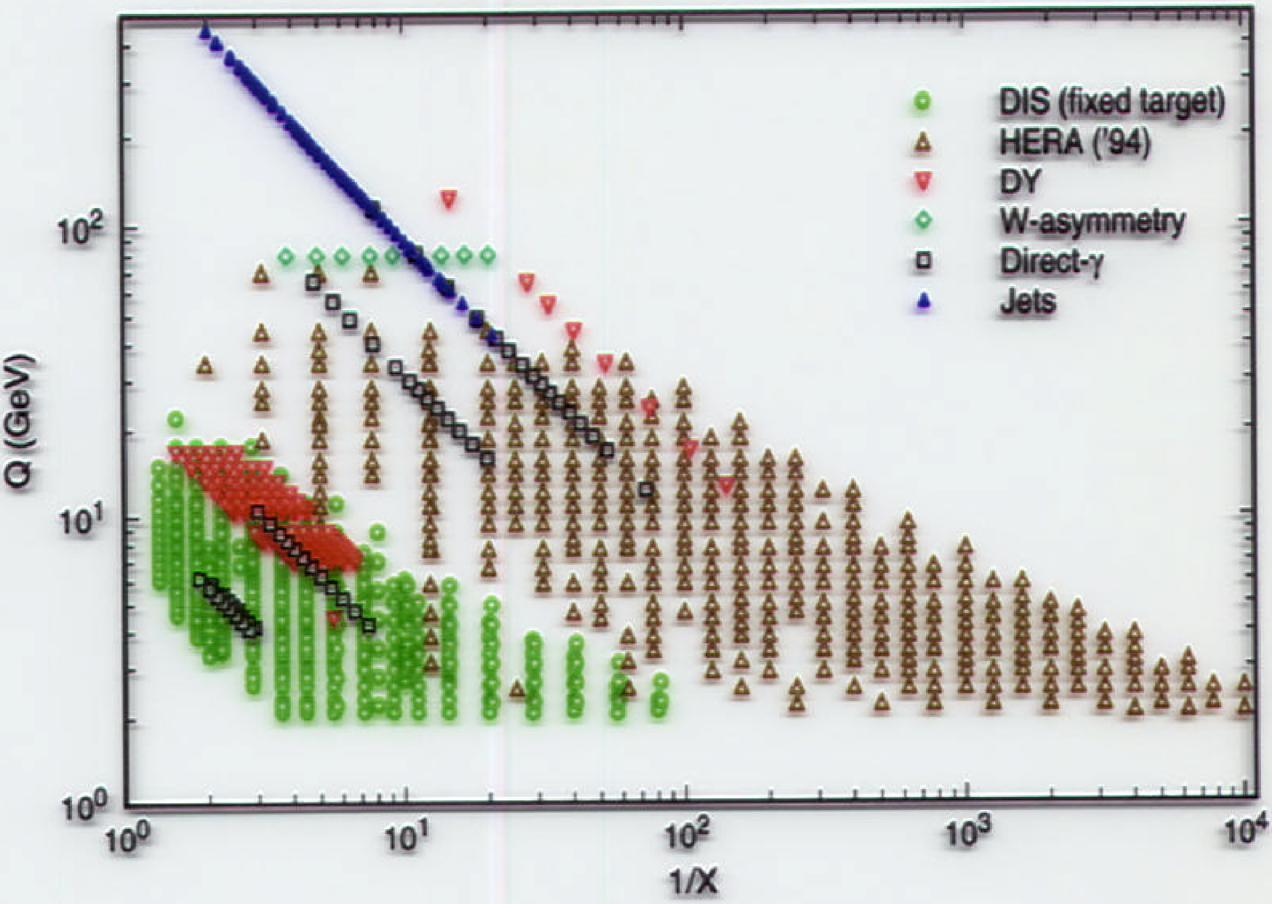
- Global fit to all observables in the SM provides $\alpha_S(M_Z) \sim 0.119 \pm 0.006$ under SM running
- Light gluino and light bottom squark modify $\alpha_S(M_Z)$ determined by extrapolation from experiments at energies below $m_{\tilde{g}}$
- β function of (SUSY) QCD:

$$\beta = \frac{g^3}{16\pi^2}\left[-11 + \frac{2}{3}n_f + \frac{1}{6}n_s + 2\right]$$

- The QCD running of $\alpha_s(Q)$ is slowed
  - $\widetilde{b}$ (color-triplet scalar) contributes little to the running
  - $\widetilde{g}$ (color octet fermion) much more significant
- Shift of 0.007 to $\alpha_S(M_Z) \simeq 0.125$, within the range of uncertainty but towards the upper end
- Separate issue concerning α_S is gauge-coupling unification: for gluinos of mass in the hundred GeV range, $\alpha_S(M_Z)$ predicted from unification is > 0.13, but 15 GeV gluinos reduce the value to ≤ 0.127, in better agreement

INFLUENCE ON PARTON DENSITIES

- Kinematic range in the (x, Q^2) plane of data included in a typical global analysis of parton densities



- Slower running of $\alpha_s(Q)$ means a slower evolution of parton densities at small x, an effect that might be seen in HERA data for $Q > m_{\tilde{g}}$. Under investigation
- Presence of scalar $\tilde{b}$ in the proton breaks the Callan-Gross relation and yields a non-zero leading-twist longitudinal structure function $F_L(x, Q)$

5 d) R and Angular Distributions in $e^+e^- \to$ jets

- Deviations of R from SM expectations at large $\sqrt{s}$?

$$R = \frac{e^+e^- \to \text{hadrons}}{e^+e^- \to \mu^+\mu^-}$$

- Scalars are produced in a p-wave coupled to the intermediate photon
  - Thresholds turn on slowly
  - Cross sections are small ($\sim 1/4$ a fermion of the same charge)
- Compared to "everything else" $\widetilde{b}$ contributes

$$\left(\frac{1}{3}\right)^2 \frac{1}{4} \quad vs \quad 2\left(\frac{2}{3}\right)^2 + 3\left(\frac{1}{3}\right)^2$$
$$\frac{1}{36} \quad vs \quad \frac{11}{9}$$

- Data must be accurate to a few % to discriminate
- Angular distributions are potentially more powerful, $\sin^2\theta$ vs. $(1+\cos^2\theta)$; data not inconsistent with a single pair of charge-$1/3$ squarks along with 5 flavors of $q\bar{q}$ pairs; $(1+\alpha\cos^2\theta)$, with $\alpha \simeq 0.92$

5 e) $\tilde{b}$-onia

- Could be seen as mesonic resonances in $\gamma\gamma$ reactions (i.e., $e^+e^- \to e^+e^-X$) and in $p\bar{p}$ formation, with masses in the 4 to 10 GeV range and $J^P = 0^+, 1^-, 2^+, ...$
- Could show up as narrow states in $\mu^+\mu^-$ invariant mass spectra at hadron colliders, between the J/ψ and Υ
- At an e^+e^- collider, the intermediate photon requires production of a $J^{PC} = 1^{--}$ state.
  - Bound states of low mass squarks with $Q_{\tilde{q}} = 2/3$ studied by Nappi with a potential model (Phys. Rev. D25, 84 (1982))
    * $\Gamma_\ell \sim 24$ eV
    * $\Gamma_h \sim 18$ keV
    * $\Gamma_{1S+\gamma} \sim 65$ keV
  - The $1S$ state decays hadronically
  - Because the leptonic decay widths are too small there are no bounds for $m_{\tilde{q}} > 3$ GeV, $Q_{\tilde{q}} = 2/3$
  - For bottom squarks, the situation is stronger ($Q_{\tilde{q}} = -1/3$).

5 f) Alternative Scenarios

- Suppose only the $\tilde{b}$ is light
  - Assume $\tilde{b}$ decay products (e.g., τc via R-parity violation) are similar to those in b decay
  - $\sigma_{\tilde{b}\bar{\tilde{b}}} \simeq \sigma_{b\bar{b}}$ for $m_{\tilde{b}} \simeq 3$ GeV
  - Fails: excess in J/Ψ channel not produced, and p_{Tb} spectrum not reproduced
- Light $\tilde{b}$ and light $\tilde{g}$, with $m_{\tilde{b}} + m_b > m_{\tilde{g}}$ but $m_b < m_{\tilde{b}} < m_{\tilde{g}}$
  - $\tilde{g} \to \bar{\tilde{b}} s$ or $\tilde{g} \to \tilde{b} d$; $\tilde{b} \to b\tilde{\chi}^0$ (light $\tilde{\chi}^0$)
  - Requires FV coupling $\tilde{g} - \tilde{b} - s$ to suppress $\tilde{g} \to g\tilde{\chi}^0$
  - Killer: $\sigma(b + \bar{b} + \not{E}_T)$ much too large; excluded at run I

6. Summary

- There is room in the measured bottom quark production rate at hadron colliders for new physics
- We postulate the existence of light gluinos and light bottom squarks with 100% branching fraction $\tilde{g} \Rightarrow b\tilde{b}$
  - $m_{\tilde{g}} \simeq 12$ to 16 GeV; $m_{\tilde{b}} \simeq 2$ to 5.5 GeV
- Our SUSY scenario with $\sigma_{\tilde{g}\tilde{g}}/\sigma_{\rm qcd} \sim 1/3$ helps to explain the magnitude and shape of the $b\, p_T$ distribution at the Tevatron
- bb and $\overline{bb}$ pair production predicted
  - Visible as a mismatch of B^0 oscillation parameters at the Tevatron and at b factories
  - Tevatron run I $\bar{\chi}$ data help constrain gluino mass
  - Should see B^+B^+ events at run II
- Search for $\tilde{b}$-onia
- b cross sections at HERA and LEP ($\gamma\gamma \Rightarrow b\bar{b}$) bear watching
- Interesting SUSY consequence: light $\tilde{t}$
- $h^0 \rightarrow \widetilde{b}\widetilde{b}^*$ dominates : could modify Higgs bounds

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